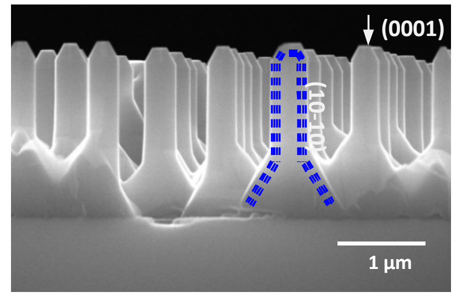
SAND2012-1775P

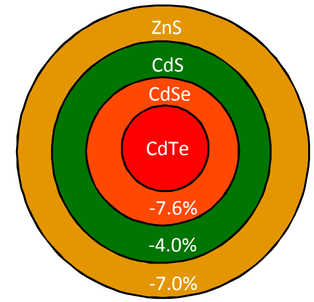
SSLS EFRC Research Challenges

Materials Architectures

1: Nanowires (George Wang)



2: Quantum Dots & Phosphors (Jim Martin)



Light Emission Phenomena

3: Competing Rad & Non-Rad Processes (Mary Crawford)

Power-conversion efficiency · Joule efficiency · Injection efficiency · Internal quantum efficiency (ε_{IQE}) · Extraction efficiency

$$\varepsilon = \varepsilon_{Joule} \cdot \varepsilon_{inj} \cdot \frac{BN^2}{AN + BN^2 + CN^3 + \ldots} \cdot \varepsilon_{ext}$$

4: Defect-Carrier Interactions (Andy Armstrong)

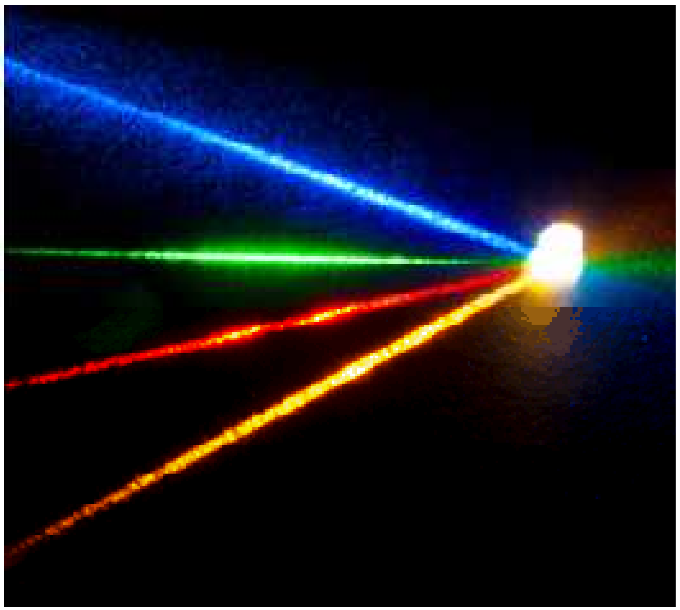
5: Enhanced Spontaneous Emission (Igal Brener)

6: Beyond Spontaneous Emission (Art Fischer)

Art Fischer
PI

Research Challenge 6: Beyond Spontaneous Emission

Exploring coherent light sources for ultra-efficient solid-state lighting: understanding their potential and limitations



Art Fischer, Igal Brener*, Weng Chow*, Dan Koleske*, Qiming Li*, Willie Luk*, Jeff Tsao*, George Wang*, Jon Wierer*, and Jeremy Wright*
Sandia National Labs

Steve Brueck* and Alexander Neumann
University of New Mexico

Yoshi Ohno and Wendy Davis
NIST – Gaithersburg

Alexander Carmele, Julia Kabuss, Martin Richter, and Andreas Knorr
Technical University of Berlin

*Participants in other Research Challenges

U.S. DEPARTMENT OF ENERGY

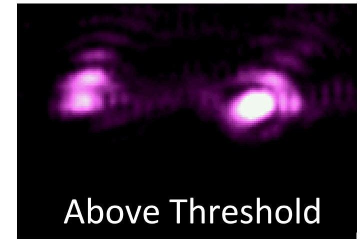
National Nuclear Security Administration

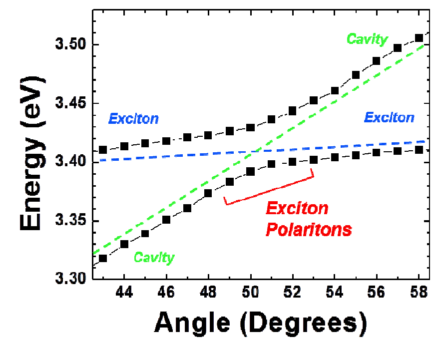
Work at Sandia National Laboratories was supported by Sandia's Solid-State-Lighting Science Energy Frontier Research Center, funded by the U.S. Department of Energy, Office of Basic Energy Sciences. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

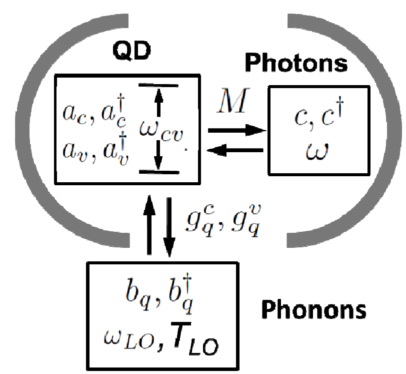
NIST THE UNIVERSITY of NEW MEXICO Sandia National Laboratories

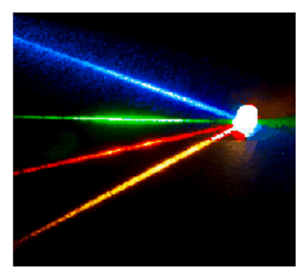
Outline of Talk

- **Introduction and Motivation**
  - Why go "Beyond Spontaneous Emission" ?
- **Human Factors Study**
  - Built a four color laser illuminant
- **Nanowire Lasers**
  - Multi-mode and single mode operation
- **Polariton Lasers**
  - RT strong coupling for GaN microcavities
- **Strong Coupling Theory**
  - Phonon interactions, coherence control
- **Future Directions**





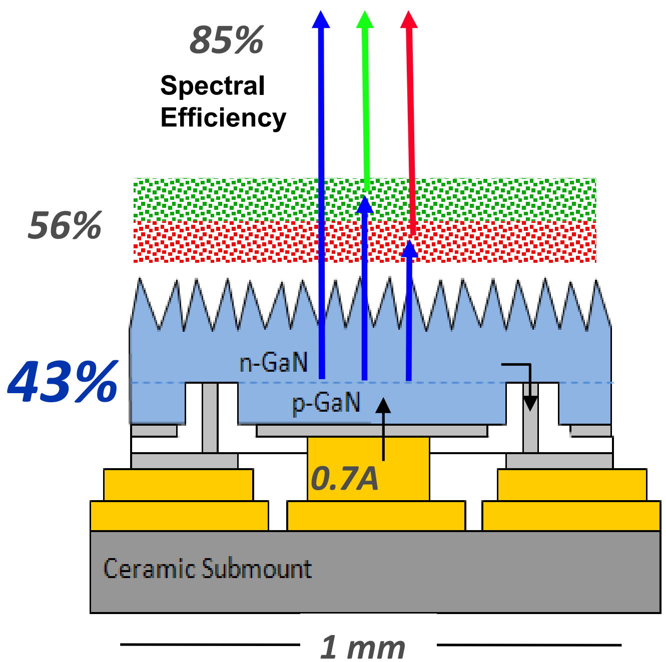




SSL Efficiency: near 100% efficiency ?

State of the art white light emitter

SSL is only 20% efficient
- Blue InGaN LEDs → 43%

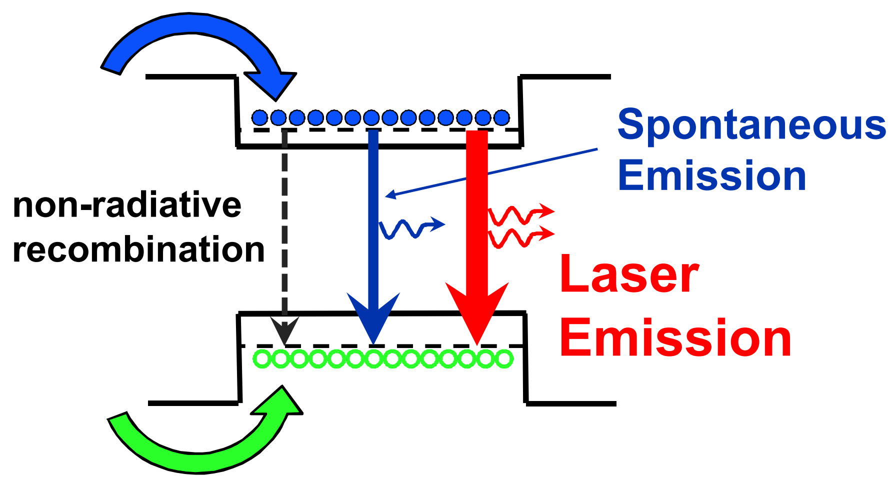


SSL Technology Grand Challenges

1 Droop : near 100% efficiency at all currents

2 Green-Yellow Gap : near 100% efficiency at all wavelengths

InGaN light emission processes:



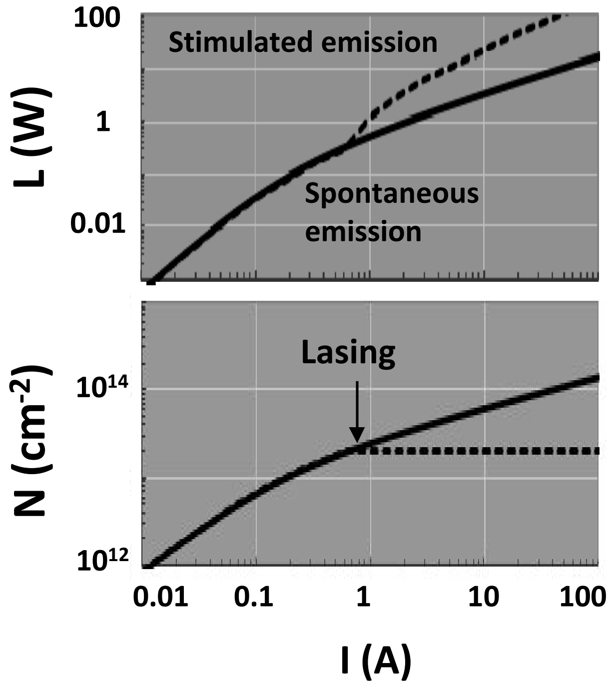
Beyond spontaneous emission…
Use a very fast light emission process !

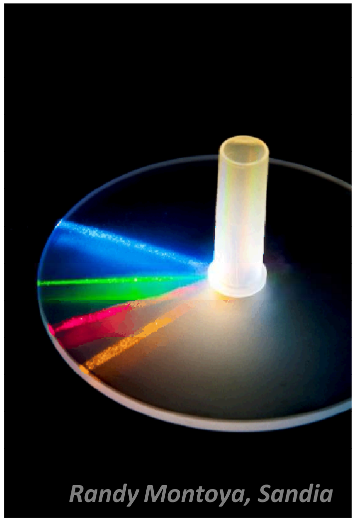
Lasers for Solid State Lighting

Advantages of lasers for lighting:

- Lasers show very high efficiency at high power
- LED and LD current densities are converging
- Carrier density is clamped at threshold
  - Circumvent the droop problem in LEDs
  - Need to reduce threshold to avoid losses
- After threshold slope efficiency is one
- Directionality, polarized emission, modulation

Clamped carrier density



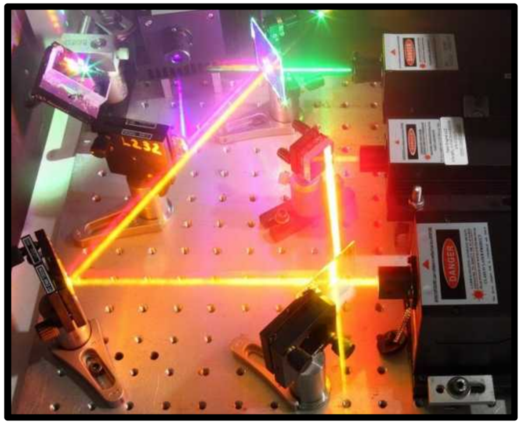


Laser Sources For SSL:

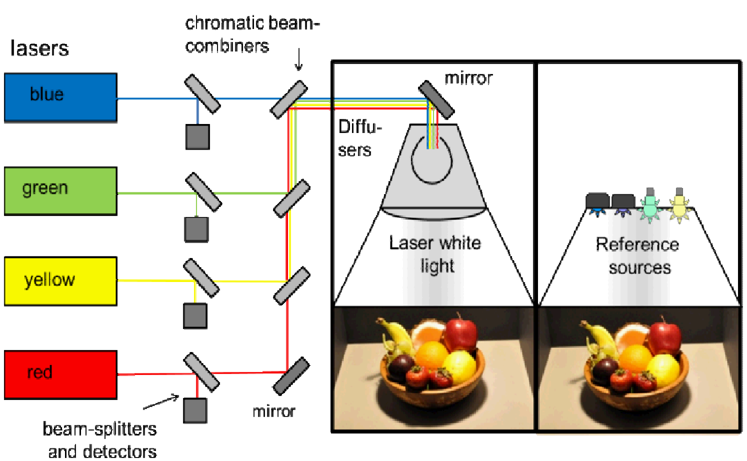
- **High efficiency**
- **Low threshold**
- **Focus on III-nitrides**
- **Nanowire lasers**
  - **Low threshold**
- **Polariton lasers**
  - **Ultralow threshold**
  - **New physics**

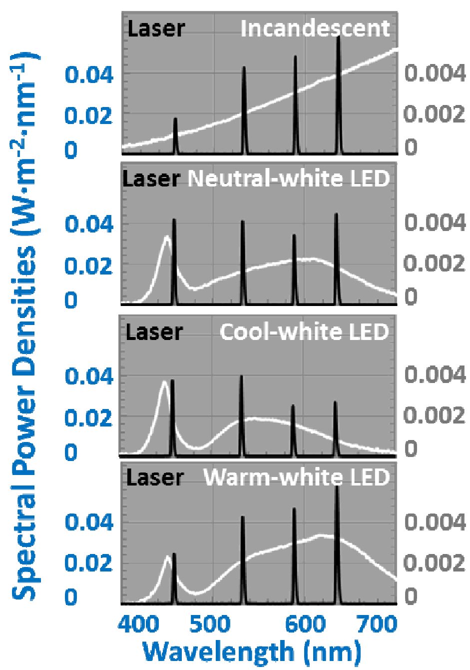
Are narrow linewidth sources acceptable?

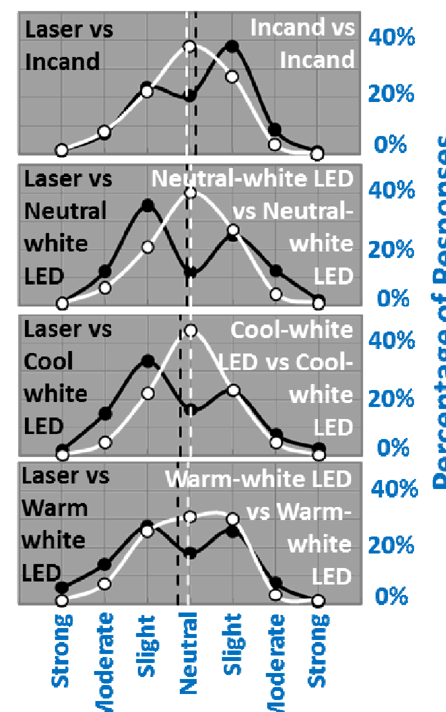
Human Factors Study: RYGB Laser Illuminant



- Constructed an RYGB laser white-light source
  - Compare Laser, Incandescent, and LEDs
- Laser sources are virtually indistinguishable from broadband sources
- Paves the way for serious consideration of lasers for SSL



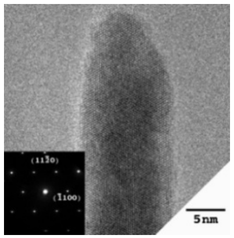


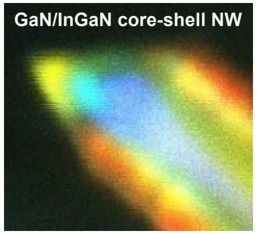


Poster: Four color laser white illuminant → Jeff Tsao

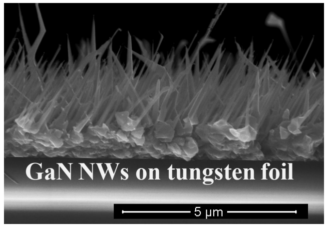
Conventional Nanowire Lasers

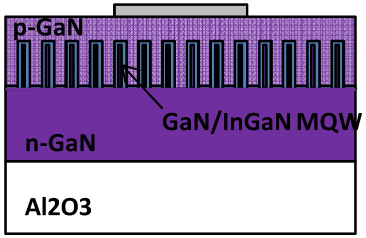
Advantages of Nanowires
- Few or no threading dislocations
- Possibility of very high IQE
- Reduced piezoelectric strain
- Wider range of alloy compositions are possible
- High efficiency green and yellow emitters



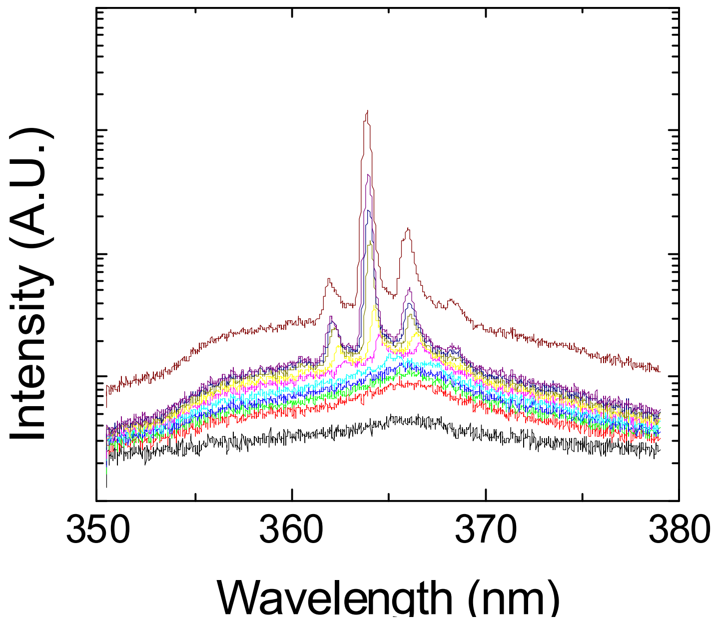


Why Nanowire Lasers?
- *Nanowire forms a low loss optical cavity*
- *Low threshold due to small mode volume*
- *Circumvent droop using NW stimulated emission*
- *Possibility of high efficiency lasers at green and yellow wavelengths*
- *Scale to small diameter for single-mode operation*

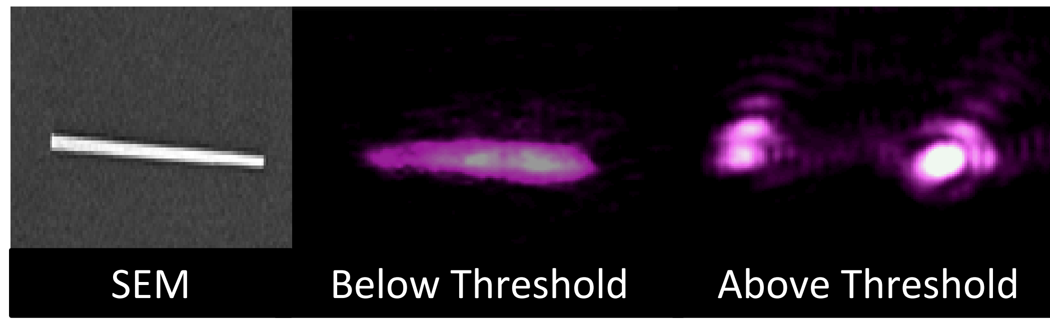




Nanowire Lasers: Multimode Operation



Poster: Lasing from III-V Nanowires
→ Jeremy Wright

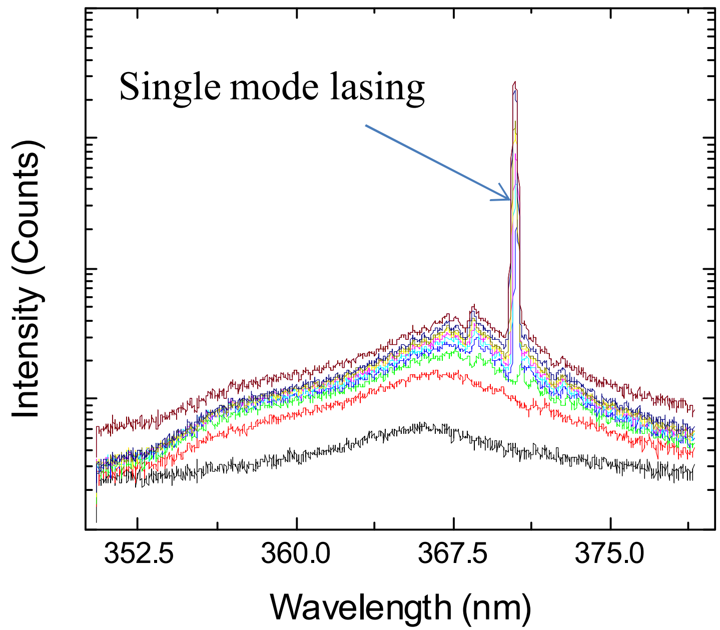


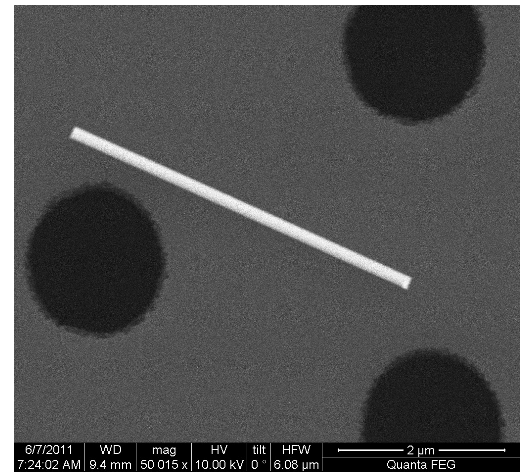
Nanowire dimensions: ~**500 nm** x 4.7µm

Optically-pumped Nanowire Laser

- **Pump laser: 266nm, 8 kHz rep. rate, 800 ps pulse**
- **Larger diameter wires typically lase multi-mode**
- **Multi-mode linewidth ~ 5 nm, threshold ~ 500 kW/cm^2**
- **Gain calculations and modal simulations to help understand laser operation**

Nanowire Lasers: Single Mode Operation





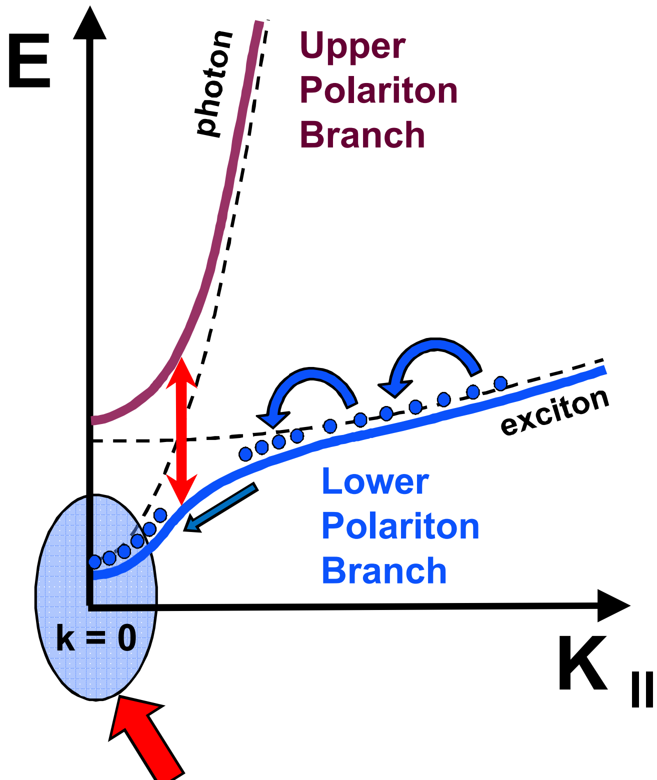
Nanowire dimensions:
~130nm x 4.7μm

Optically-pumped Nanowire Laser

- **Smaller diameter wires lase single mode**
- **Narrow linewidth < 0.1 nm, threshold ~ 250 kW/cm^2**
- **>18 dB side mode suppression ratio**
- **Single mode operation is more desirable**
  - **No mode hopping, lower noise, stable far-field patterns**
  - **Lower threshold operation**

GaN-based polariton light source

Polariton Dispersion Curves



Polariton Condensate

Exciton → Bound state of an electron-hole pair

Polariton → Strongly coupled mixed state of a cavity photon and an exciton.

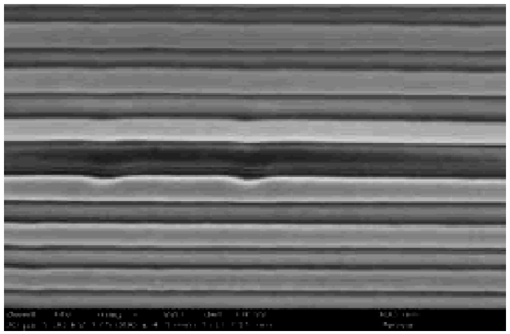
Why Study Polariton Lasers?

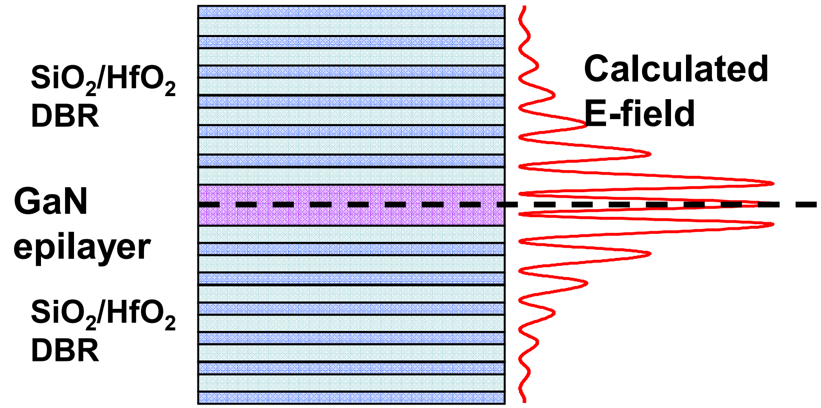
- Threshold is 2 – 3 orders of magnitude lower than photon lasers.
  - 2 x 10^{16} cm^{-3} → University of Michigan
  - 2 x 10^{18} cm^{-3} → South Hampton, EPFL
- Operate at a density below the turn on of droop.
  - 1 - 5 x 10^{18} cm^{-3} → Droop becomes important
- Investigate new physics in strong coupling regime.
  - Polariton condensates, BEC, etc.
  - Photon-like wavefunction can extend past crystal defects to avoid non-radiative recombination.

Polariton Laser → Fast Photon Emission

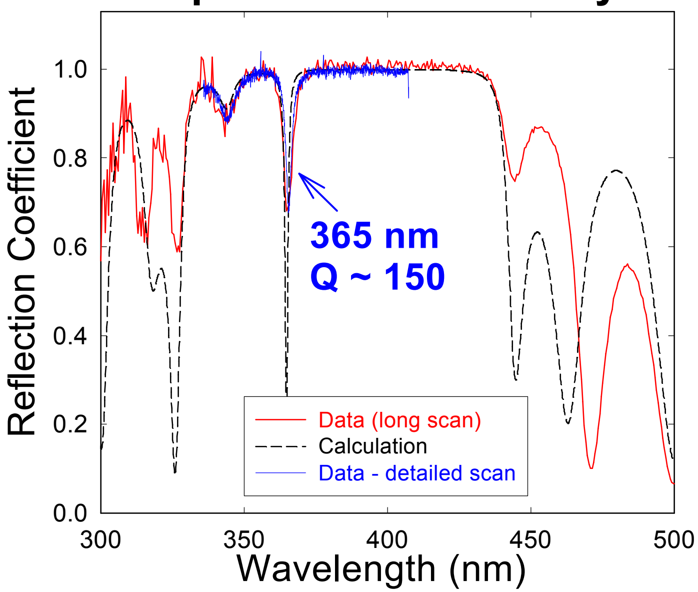
1D GaN Microcavities: Introduction

FIB-SEM image → 1D HfO_2/SiO_2 cavity

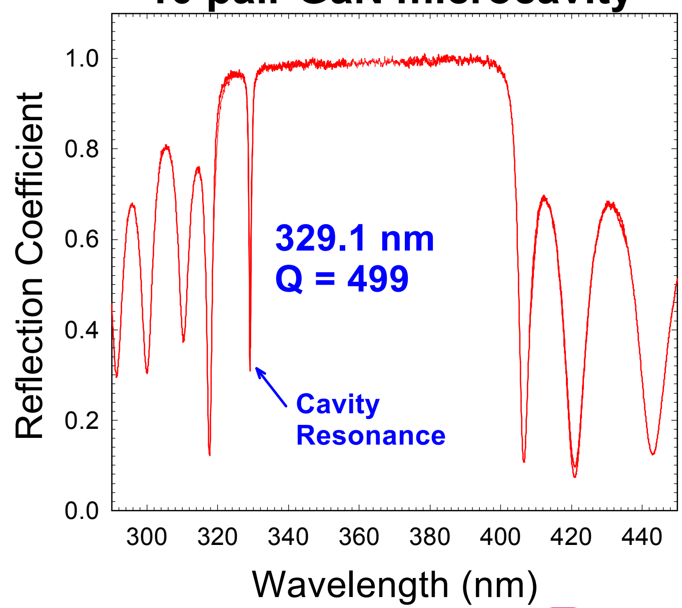




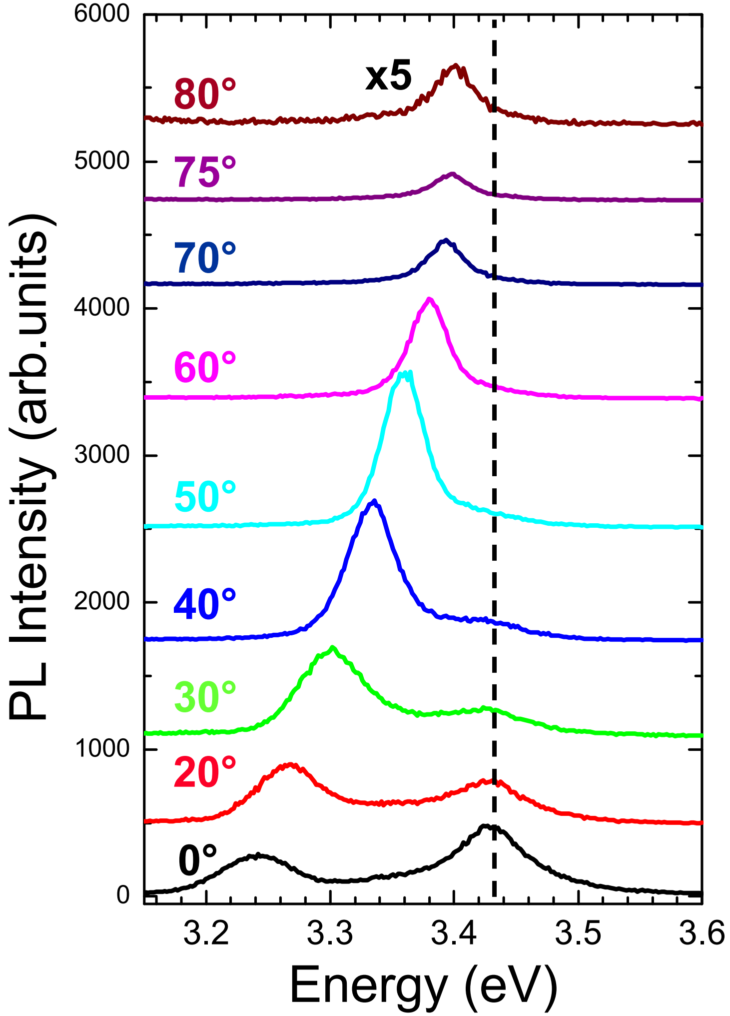
8 pair GaN microcavity



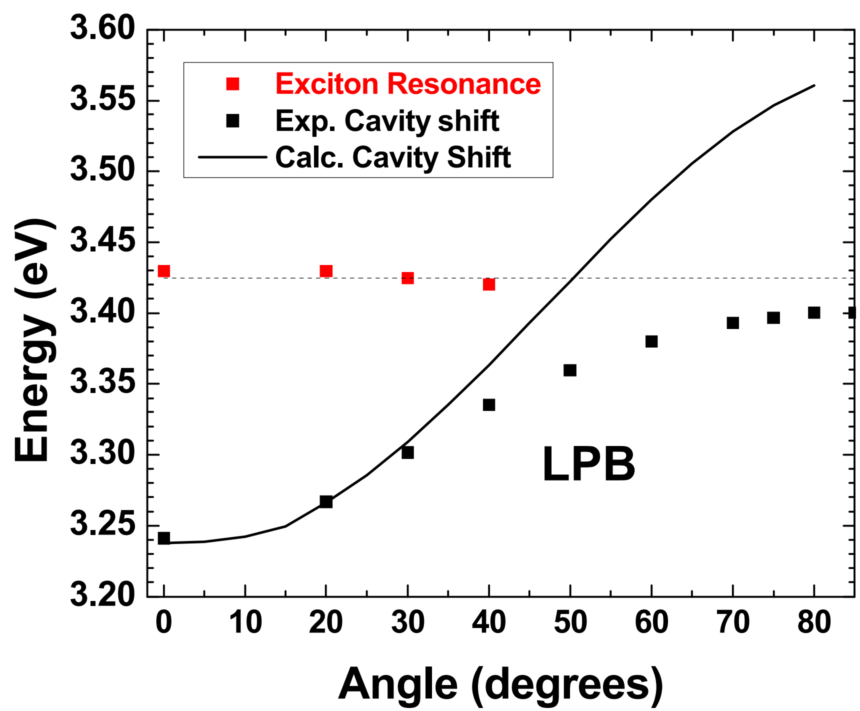
10 pair GaN microcavity



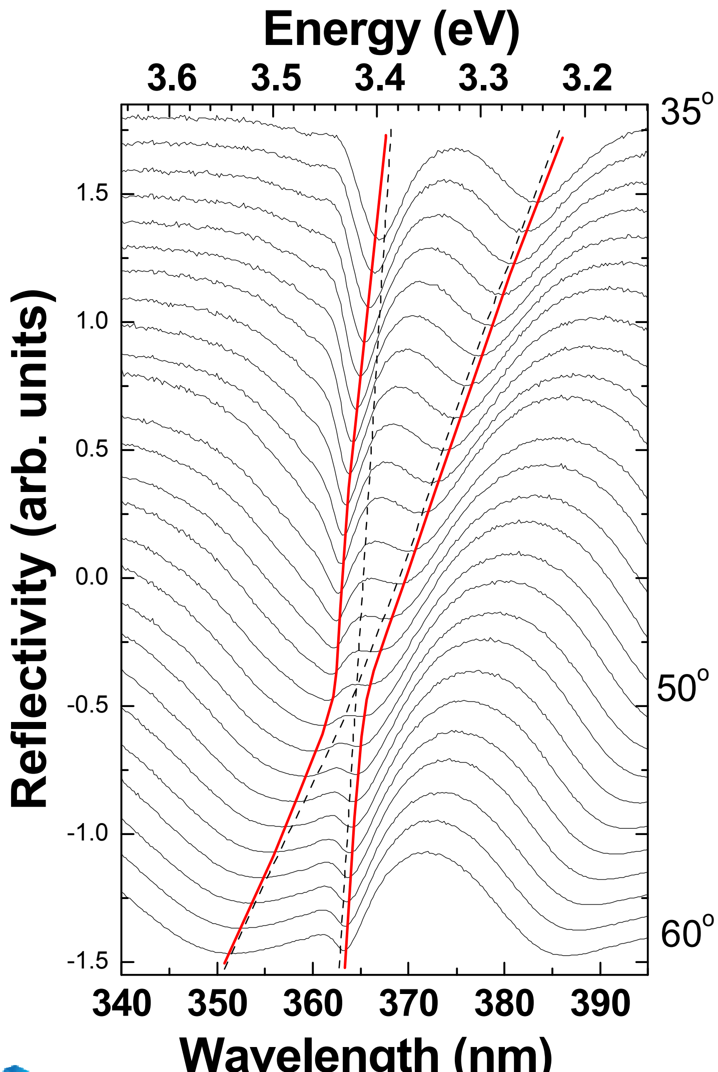
Angle-resolved PL (5 pair, 2λ cavity)



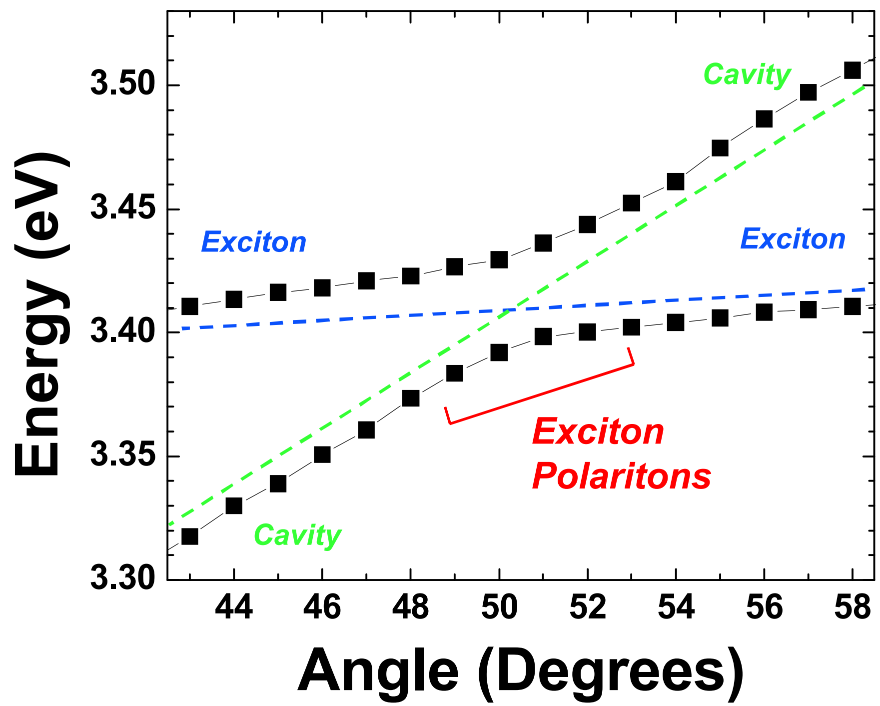
- Angle-resolved PL is used to map k-space
- 5 pair HfO_2/SiO_2 DBRs – 2λ cavity
- No cavity resonance observed above bandgap
- Upper polariton branch is more difficult to see



Angle-resolved Reflectivity (8 pair, λ cavity)



- Angle-resolved Reflection maps out k-space
- 8 pair HfO_2/SiO_2 DBRs – one λ cavity
- Two dips observed at all angles
- Observed Rabi splitting of 37.5 meV
- Goal: RT electrically-injected polariton laser



NIST THE UNIVERSITY of NEW MEXICO Sandia National Laboratories

Modeling: Strongly Coupled QD-Photon-Phonon System

All investigations based on Sandia/TU developed model for strongly-coupled QD-photon-phonon system

- Carmele, Richter, Chow and Knorr, PRL **104**, 156801 (2010)
- Carmele, Kabuss, Richter, Richter, Knorr & Chow and Knorr, J. Modern Optics 58, 1951 (2011)

Sandia National Labs -- EFRC

Weng Chow

Technical University, Berlin -- SFB 787 funding

Alexander Carmele – Student/Posdoc

Ph.D. dissertation (2010) research related to EFRC strong coupling task

Carl-Ramsauer Prize for outstanding doctoral dissertation in the field of physics

Julia Kabuss – Student

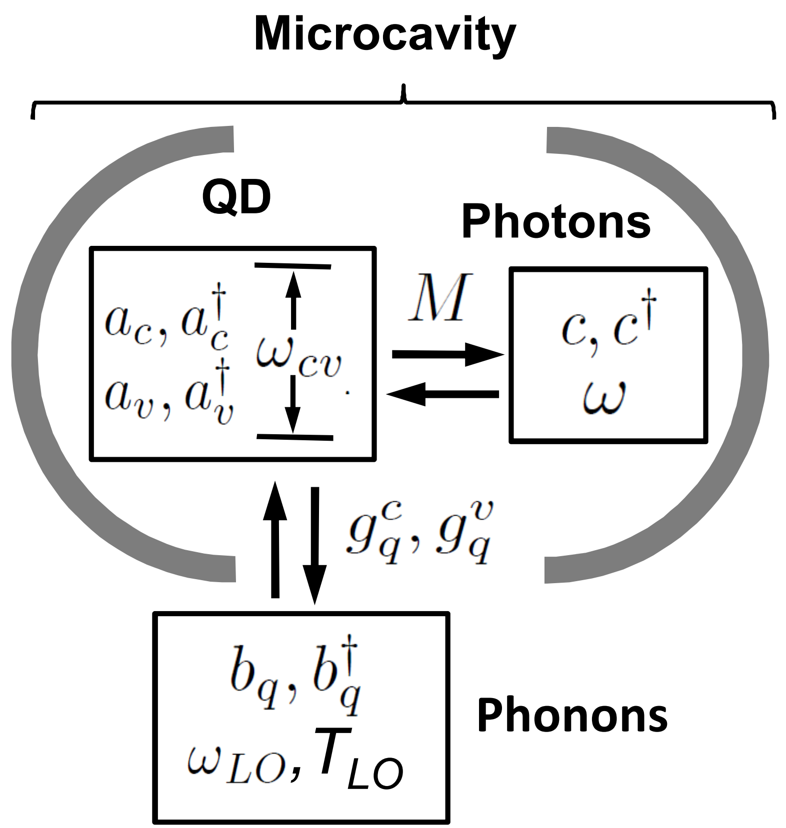
Ph.D. expected completion Fall, 2012

Research on quantum coherence and phonon physics in strongly coupled systems

Andreas Knorr – Professor of Theoretical Physics

Collaborator since 1990

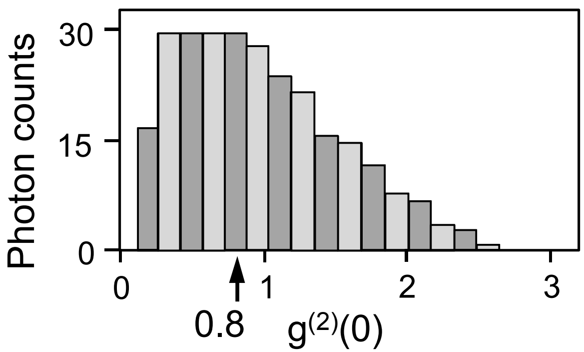
Collaborated on first III-gain theory paper (APL, 1995).



Modeling: Strongly Coupled Systems

1) Photon antibunching in strongly-coupled QD-photon-phonon system

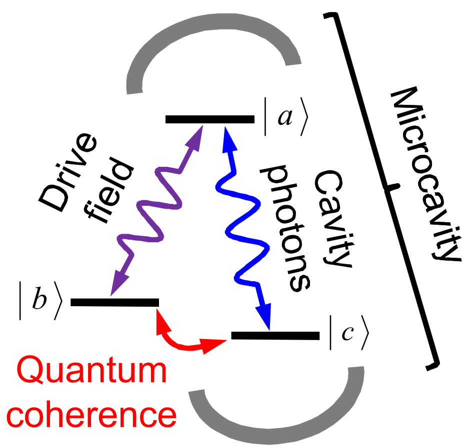
- Carmele, Richter, Chow and Knorr, PRL **104**, 156801 (2010)



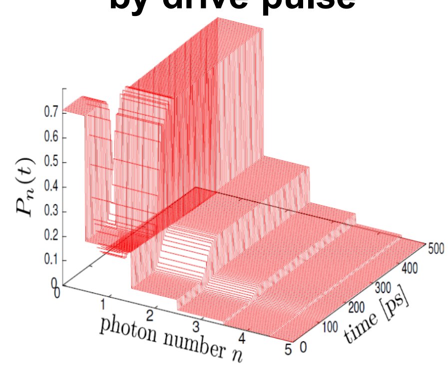
- Nonclassical (better than laser) intensity correlation
- Potential Application : Room temperature single-photon sources

2) Using quantum coherence to control strong coupling

- Kabuss, Carmele, Richter, Chow and Knorr, physica status solidi B 248, 872 (2011)



Photon statistics change by drive pulse



Potential Applications

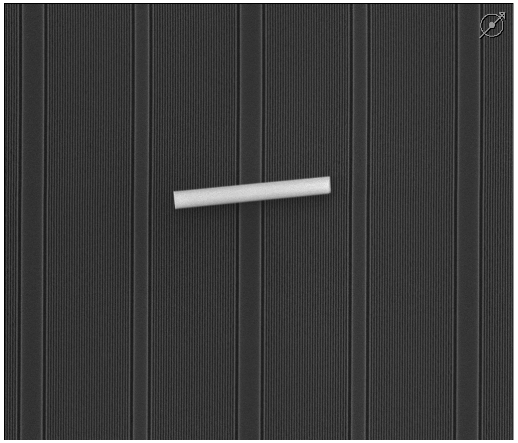
- Photon-on-demand sources
- Fundamental efficiency limit of PVCs

Summary: Research Highlights

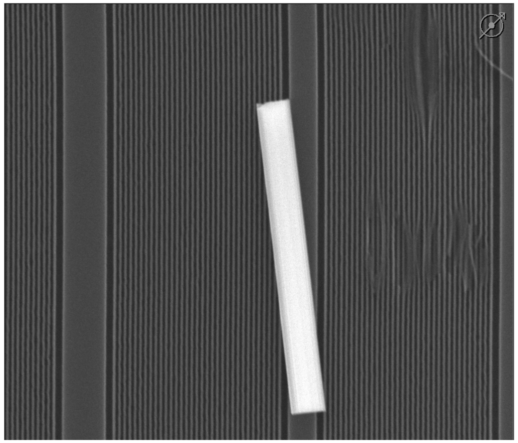
- Experimental demonstration that four-color laser white light can be illuminant quality
- Demonstrated a low-threshold single-mode GaN nanowire laser*
- Observed room temperature strong coupling and polaritons in a 1D GaN microcavity
- Developed a new theory for strong coupling in emitter-photon-phonon systems → non-classical sources.

*Synergistic with other Research Challenges

Future Work: DFB Nanowire Lasers



Wires are placed on gratings with random orientations.



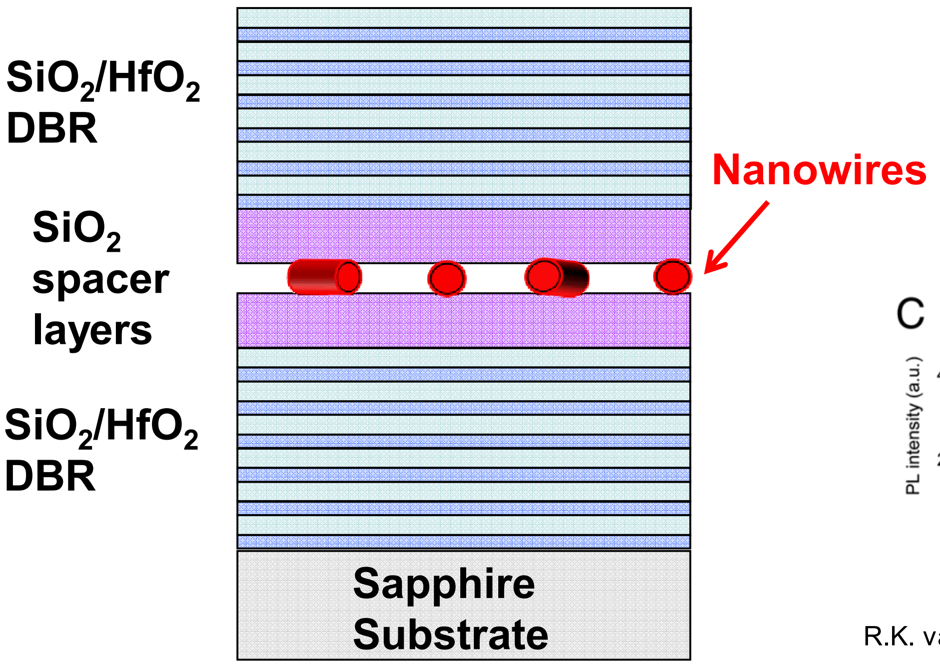
The wire is then rotated to minimize optical feedback.

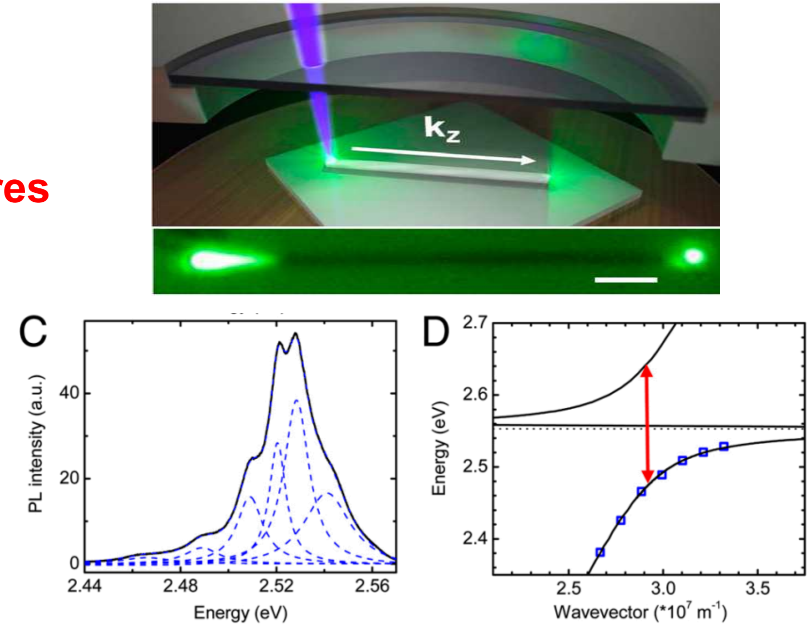
The wire is finally rotated to maximize optical feedback.

- Nano-grating will help to select a single axial mode.
- The lasing threshold may be lowered from additional reflectivity due to the relatively low end facet reflections.
- Bragg reflectors are used in VCSELS for high reflectivity and used in in-plane lasers for frequency selectivity.

Future Work: GaN Nanowire Polariton Lasers

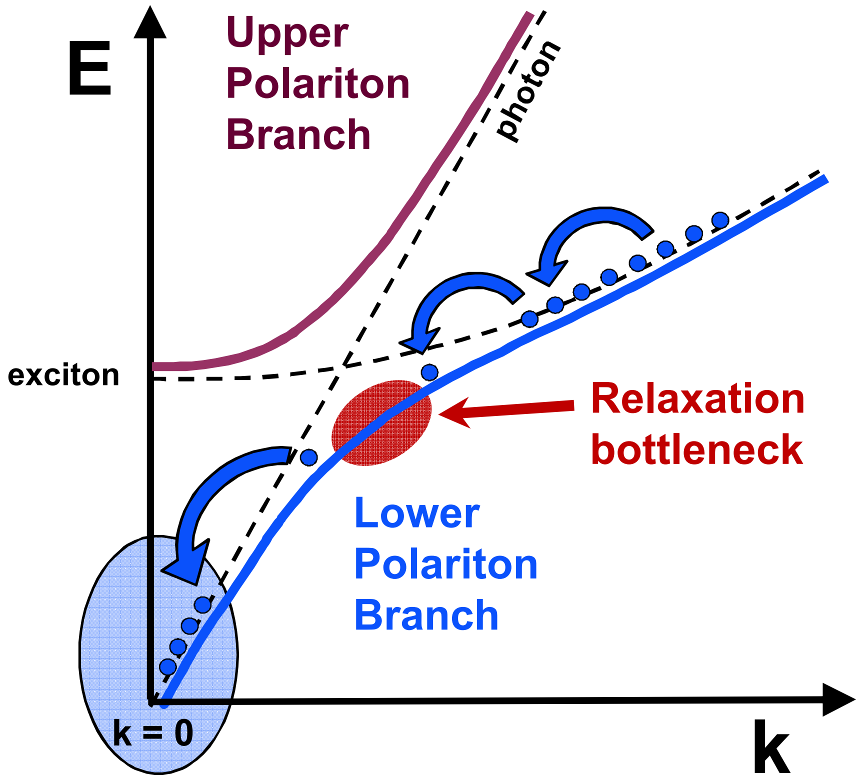
- **Nanowires incorporated into one-dimensional DBR cavities**
  - **GaN nanowires as a platform for polariton studies**
  - **Nanowires are defect free, narrow linewidth emitters**
- **Use the nanowire as the cavity**
  - **GaN nanowire micro PL → polariton effects**
  - **Easier method of demonstrating strong coupling**





R.K. van Vugt et al., Proc. National Academy Sciences **108,** 10051 (2011)

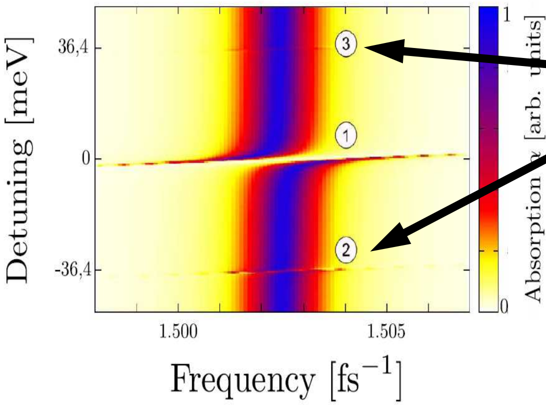
Future Work: Study GaN Polariton Relaxation Dynamics



Study polariton relaxation dynamics

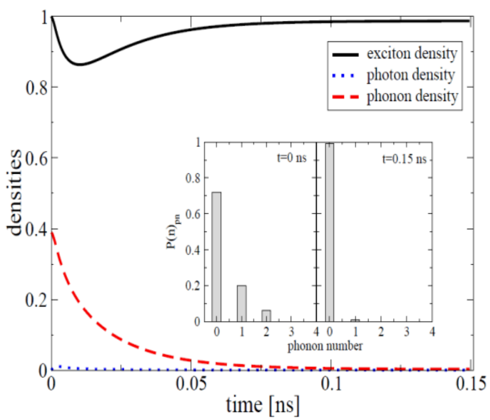
- Measurements for GaN and InGaN
- Measure lifetime for different parts of dispersion curve
  - Exciton-like vs photon-like
- Investigate Phonon Bottleneck
  - Must overcome relaxation bottleneck
  - Polariton-polariton scattering
  - Room temperature phonon scattering
- Time-Resolved Photoluminescence measurements
  - Time-correlated single-photon counting
  - Streak Camera measurements

Future Work: Explore anti-Stokes phonon-assisted strong coupling



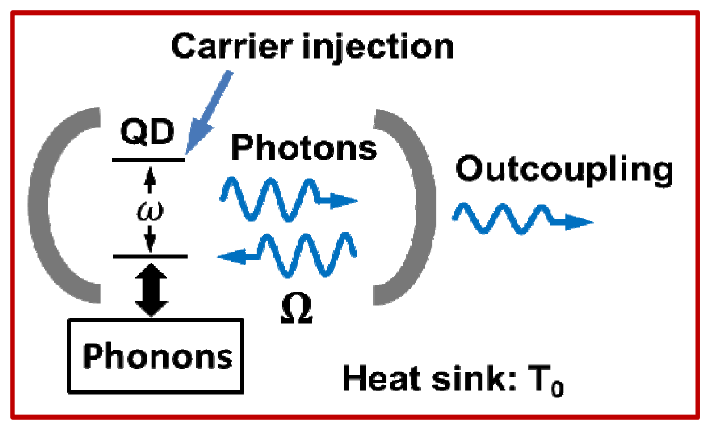
Discovered under EFRC: Anti-crossings at detunings of +/- one LO phonon energy

- Carmele, Kabuss and Chow, submitted to Optics Express



Also discovered that phonon-assisted strong-coupling can change phonon population and statistics

Substrate temperature



Explore <u>improving LED efficiency with self-cooling</u> by anti-Stokes ($\omega > \Omega$), phonon-assisted strong coupling

Summary: Future Directions

- Fundamental limits to efficiency of lasers for SSL
- Conventional nanowire lasers: DFB, photonic crystal*
- GaN-based nanowire polariton lasers: nanowire, DBR cavity*
- Explore anti-stokes phonon-assisted strong coupling
- Investigate polariton relaxation dynamics for GaN materials
- Demonstrate GaN polariton condensates (polariton lasing)

*Synergistic with other Research Challenges